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Photoconduction and photovoltaic effects in Pentacene based on thin film organic phototransistor

S. Mansouri[a,b],*, A. Jouili[a], A. Dere[c], L. El Mir[a], Abdullah G. Al-Sehemi [d-f], Ahmed Al-Ghamdi[g], Z. Şerbetçi[h], F. Yakuphanoglu[i]

[a] Laboratory of Physics of Materials and Nanomaterials applied at Environment: LaPhyMNE, Faculty of Sciences in Gabes, Gabes University, Erriadh City, Zrig, 6072 Gabes, Tunisia
[b]Faculty of Sciences and Technical in Sidi Bouzid, Kairouan Uninіversité University, Tunisia
[c]Nanoscience and Nanotechnology Laboratory, Firat University, Elazig, Turkey
[d]Department of Chemistry, Faculty of Science, King Khalid University, Abha 61413, P.O. Box 9004, Saudi Arabia
[e]Research Center for Advanced Materials Science, King Khalid University, Abha 61413, P.O. Box 9004, Saudi Arabia
[f]Unit of Science and Technology, Faculty of Science, King Khalid University, Abha 61413,P.O. Box 9004, Saudi Arabia
[g]Department of Physics, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia
[h]Department of Chemistry, Faculty of Sciences and Arts, Bingol University, Bingol, Turkey
[i]Department of Physics, Faculty of Science, Fırat University, Elazığ, Turkey

In this paper, Pentacene thin film phototransistors were fabricated and characterized. The magnitude of the photocurrent induced by illumination was found to be the result of two distinct effects: photovoltaic effect, which the photocurrent related to electron-hole pair generation, and photoconductor effect, that the current enhancement caused by a threshold voltage shift. The electrical parameters such as mobility μ, threshold voltage Vth, the Ion/Ioff ratio, the subthreshold S, the interface density of trap Dit, the total trap density Ntrap, and the photoresponse R value were determined. The effect of white light illumination where investigated.

Keywords: Pentacene thin film; phototransistors; photoconductivity; photovoltaic; photoresponsivity.

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Corresponding authors: mansourislah@gmail.com (S. Mansouri)

1. Introduction

In recent years, many researches in the field of organic thin film transistor to ameliorate the electrical parameters of this component, for use then in electronic circuits. Electronic devices based on organic semiconductors such as conjugated polymers have attracted much attention due to their low cost, ease of processing and variety of applications. Prominent examples of organic microelectronic devices are OTFTs can potentially be developed into light-weight, flexible, and low-cost electronic devices [1]. The thin film transistors based on p-type organic semiconductors have showed the high-performance and high mobility of the order of 1 cm^2/V s [2–4], organic solar cells (OSCs) [5], organic light emitting diodes (OLEDs) [6] and organic photodiodes (OPDs) and phototransistors (OPTs) [7].

In recent years, optoelectronic researchers have well investigated organic phototransistors with an aim to replace conventional inorganic photo-detectors with these low cost devices. Output current of a phototransistor, not only depends upon the electric field which is applied at its gate terminal but also on the intensity of the light being illuminated over it. Different kinds of organic semiconducting materials were tried by various researchers around the world with different dielectric materials and device architectures in order to enhance and optimize the performance of organic phototransistors. P-Type organic semiconductors have been extensively used in organic thin film transistors applications and furthermore, high performance OTFTs can be improved by use of derivatives of pentacene, rubrene, anthracene, or thiophene[3, 4, 8, 9]. On the other hand, organic phototransistors which are type of optical transducer in which light detection and signal amplification are one of three terminal optoelectronic devices in which light can be used as an external stimulus to create photogenerated carriers in addition to the carriers induced by the gate voltage [10-13]. Organic phototransistors (OPTs) are considered to be one of the feasible applications of OTFTs because of their large absorption properties in visible light and the excellent photo current generation [14–17].

In the present work, the field-effect transistor having Pentacene as active layer was grown at room temperature. For the first time, the electrical and visible light photosensing properties of the PVP-Pentacene thin film phototransistor will be presented. The photocurrent mechanisms of the transistor are also discussed. We have exploited the output characteristics and transfers current to extract all electrical thin film parameters at room temperature and under light white illumination.

2. Experimental details

The transistor was fabricated as follows, firstly, the SiO2 layer (100 nm) having silicon wafer was chemically cleaned and dried by nitrogen. The polyvinylpyrrolidone (PVP) (70 nm) layer was coated onto SiO2 layer having silicon substrate. Then, Pentacene was evaporated on polyvinylpyrrolidone (PVP) layer using a thermal evaporation system at 10-5 Torr. The source and drain electrodes were prepared using a finger mask of 1000 µm x 50 µm by evaporation of silver. The width (W) and length (L) of the transistor are 1000 and 50 µm, respectively. Fig.1 shows the schematic structure of Pentacene thin film phototransistor. Then, the transistor was characterized by FYTRONIX 5000 TFT characterization system. The measurements (I-V) characteristics of the PVP-Pentacene thin film phototransistor were performed at room temperature under dark and various light intensities using a FYTRONIX solar simulator.

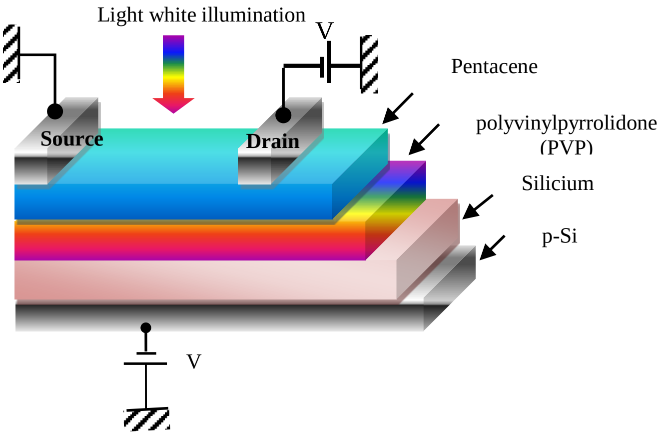

Fig. 1. *The schematic diagram of the Pentacene thin film phototransistor structure.*

3. Results and discussion:

AFM image of the Pentacene layer are shown in Fig. 2. As seen in Fig. 2, the Pentacene layer has a high surface homogeneity. The Pentacene film is formed from the particles with grain size of 150 nm.

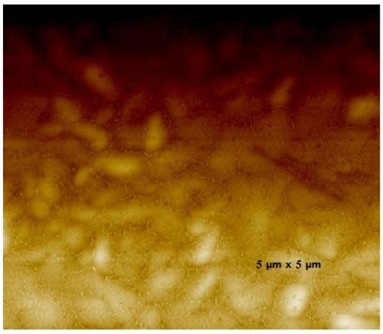

Fig. 2. *AFM image of PVP-Pentacene layer.*

Fig. 3 shows the plots of drain current vs. drain voltage of the Pentacene thin film phototransistor at various gate voltages under dark. As seen in Fig. 3, the drain current increases with drain voltage and reaches a saturation due to a pinch-off of the active channel of the transistor. For the operating of the transistor, the two silver contacts were designated as the drain and source, respectively and gate voltage is applied to the gate electrode. In this case, the drain-to-source current then flows between the Silver contacts via Pentacene organic material. The drain–source current is controlled by gate voltage. As seen in Fig. 6, the drain current of the transistor increases with drain voltage and reaches a saturation due to a pinch-off of the active channel of the transistor. At lower voltages, the drain current–voltage curves exhibit a good linearity of response. This confirms that a good ohmic contact was established between the PVP-Pentacene and silver contacts. The drain current Ids increases with Vds and saturates at higher voltages, when the gate voltage is varied between -10 and 0V. The drain current usually tends to saturate due to the pinch-off of the accumulation layer, if the drain voltage Vds is more negative than the applied gate voltage Vgs.

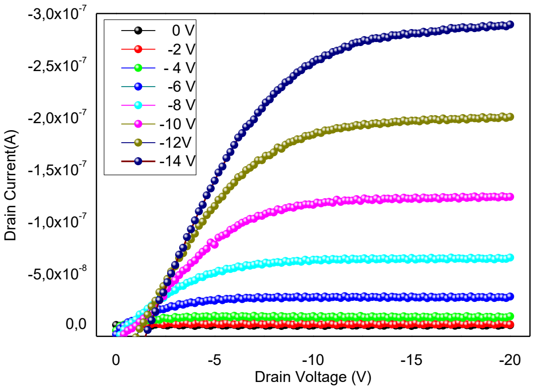

Fig. 3. *The plots (output characteristics) of drain current vs. drain voltage of the PVP-Pentacene thin film phototransistor at various gate voltages and under dark.*

The output characteristics of Pentacene thin film phototransistor at various illumination intensities are shown in Fig. 4. These measurements were performed under both turn-on and turn-off states. At turn-on state, the drain current of the transistor increases with illumination, but for turn-off state, it does not increase with light illumination. As seen in Id- Vd plots of the transistor at various illumination intensities, the effect of contact resistance Silver/ Pentacene thin film phototransistor was decreased by the increasing of the illumination intensities, because, the saturation region was decreased by the illumination intensities. The Pentacene thin film phototransistor works in a p-channel operational mode because the channel drain current increases with negative gate voltages, for that, the TFT works in a p-channel operation mode.

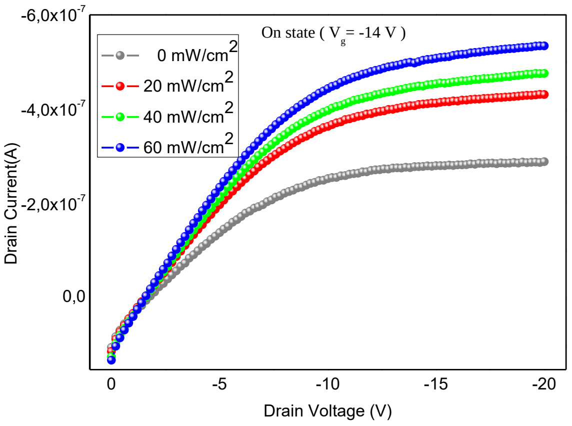

***Fig. 4.** The output characteristics of the Pentacene thin film phototransistor under white light illumination for various intensity at Vg = - 14 V.*

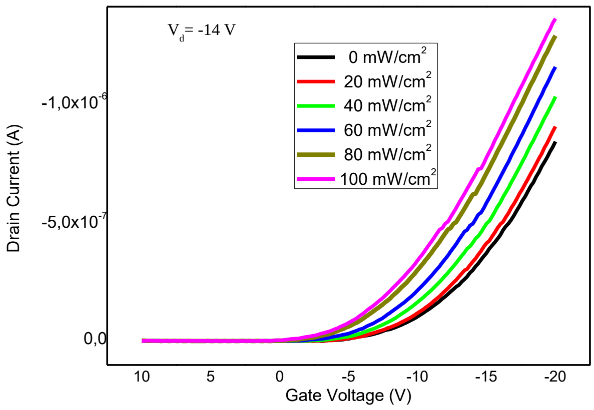

***Fig. 5**. The drain current–voltage (transfer) characteristics of the Pentacene thin film phototransistor transistor dark-white light illuminations at Vds = -14 V.*

The transfer characteristic of the Pentacene thin film phototransistor under dark-white light illuminations is shown in Fig. 5. The transfer characteristics of thin film transistors can be described by the following relations [18-20],

$$I_{ds}=\frac{W}{L}C_i\mu_{lin}\left[\left(V_{gs}-V_{th}\right)V_d-\frac{V_d^2}{2}\right],\quad \left|V_{ds}\right|<\left|V_{gs}-V_{th}\right| \quad (1)$$

$$I_{ds}=\frac{W}{2L}C_i\mu_{sat}\left(V_{gs}-V_{th}\right)^2,\quad \left|V_{ds}\right|>\left|V_{gs}-V_{th}\right| \quad (2)$$

Where Ci is the insulator capacitance per unit area (Ci = 49.33 nF/cm2), Vth is the threshold voltage and µsat is the field effect mobility in the saturation region.

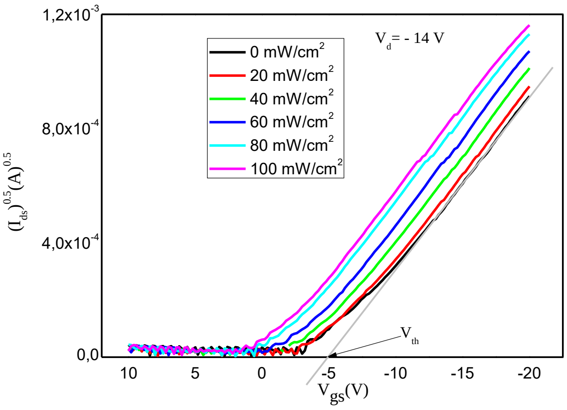

***Fig. 6.** The plot of square root of the drain current vs. gate voltage (I_ds^(1/2) –Vg) under white light illumination at Vds = -14 V.*

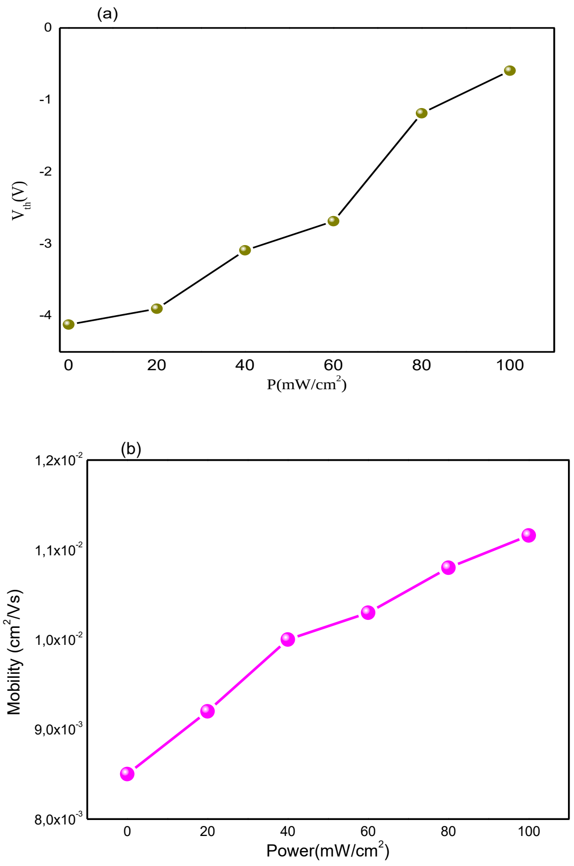

***Fig. 7**. Plot of a) threshold voltage and b) Mobility vs. P for the Pentacene thin film phototransistor.*

The plots of $I_{ds}^{1/2}$ vs. Vg under Vds=-14 V for the transistor are shown in Fig. 6. The Vth and µsat values of the PVP-Pentacene thin film phototransistor are determined from the linear region of the plot of $I_{ds}^{1/2}$ vs. Vg under Vds = -14 V. The threshold voltage and mobility dependence on illumination intensity is shown in Fig. 7 (a) and (b), respectively. The field effect mobility of the thin film phototransistor under dark was found to be 0.009 cm^2/V s. In general, the mobility of OTFTs depends on the active layer, preparation method of active layer film and morphology properties [21]. The transport charges in cannel layer of the organic phototransistors can be explained by the photoconductive and photovoltaic effects. In photoconductive state, the conductivity of channel increases with illumination due to photogenerated charges. But, photovoltaic behavior is photovoltage due to the light illumination. The photovoltage is induced by the large number of accumulated electrons under the source. As seen in Fig. 6, the values of mobility are increased with illumination intensity. But the absolute Vth values are decreased. The shift of the threshold voltage indicates a nonlinear behavior with light illumination. This nonlinear behavior is because the charge transfer at the dielectric layer/semiconductor interface is retarded by accumulated charges and this causes a lower photosensitivity at higher light intensity. Fig. 7 was fitted and the fitting exhibits an exponential increase and this confirms that the photovoltaic effect in turn-on state is dominant for the transistor. The dependence of the threshold voltage shift and mobility parameters with illumination can be expressed by the following theoretical model [22, 23]:

$$\Delta V_{th} = \frac{AKT}{G_M q} \ln\left(1 + \frac{\eta q \lambda P_{opt}}{I_{pd} hc}\right) \qquad (4)$$

And

$$\mu = \frac{I_{ph}}{qEpWD} = \frac{BP_{opt}}{qEpWD} \qquad (5)$$

where GM is the transconductance, q is the electronic charge, Popt is the incident optical power, is the quantum efficiency, hc/λ is the photon energy, Iph is the photo current, Ipd is the dark current for electrons, Vth is the threshold voltage shift, A and B are the fitting parameters, p is the hole concentration, E is the electrical field in the channel. It is evaluated that the theoretical models defined by Eqs. (4) and (5) are in agreement with obtained experimental results. The shift in threshold voltages and increase in the mobility values are explained by the generation of carrier charges by visible light. This is essential for integration of transistors into electronic circuits. The visible light photons generate positive dipoles at the semiconductor-silicon diode interface and in turn, a negative gate voltage shifts, i.e., it can be attributed to trapping of holes photogenerated at the dielectric layer/semiconductor interface of the transistor. The threshold voltage of Pentacene thin film phototransistor is reduced by 3.53 V. This reduction of the threshold voltage is significant for the electronic technology applications of organic thin film transistors.

The very important parameter of the TFT is the field effect mobility µFET which indicates how easy the charge carriers can drift under the influence of electric field. The mobility for field effect phototransistor µFET in the saturation region was determined by the following expression:

$$\mu_{FET} = \frac{2L}{WC_i}\left(\frac{dI_{ds}^{1/2}}{dV_g}\right) \qquad (6)$$

The µFET values of the Pentacene thin film phototransistor under dark and white light illuminations were determined from the plot of square root of the drain current vs. gate voltage $\left(I_{ds}^{1/2}\right)$ under Vds = -14 V as shown in Fig. 6, and are given in Fig. 7(b). As seen in Fig. 7(b), the mobility of charge carriers in the Pentacene TFT under illuminations is higher than that under dark.

As seen in Table 1, the µFET s of the Pentacene thin film phototransistor are increased from 8.5× 10-3 cm^2/Vs to 1.11× 10-2 cm^2/Vs with increasing light intensity from dark condition to 100 mW/cm2. This higher µFET of the Pentacene TFT depends on the preparation conditions such as the active layer, thickness and solvent type of the active layer, width and length of the device, deposition rate, the gate insulator, gate substrate, source and drain electrode types, surface treatment, technique methods of the active layer and morphology of Pentacene film deposited on the PVP. The shift in threshold voltages and increase in the mobility values are explained by the generation of carrier charges by illumination. This is significant for incorporation of transistors into electronic circuits. The white light photons generate positive dipoles at the organic semiconductor-PVP interface and in turn, a negative gate voltage shifts, i.e., it can be attributed to trapping of holes photogenerated at the dielectric layer/semiconductor interface of the transistor [21, 24].The higher mobility of the transistor can be attributed to the morphology of Pentacene film on the nanostructured gate dielectric layer and the dielectric PVP/surface properties of the transistor.

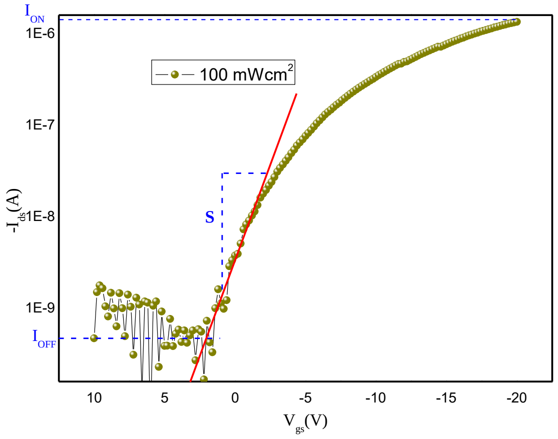

Fig. 8. *Plot of log Ids vs. Vg for the Pentacene thin film phototransistor under white light illumination at Vds = -14 V.*

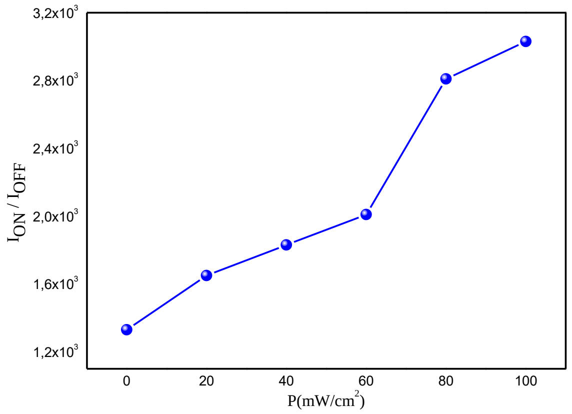

Fig. 9. *Plots of Ion/Ioff vs. P of Pentacene thin film phototransistor.*

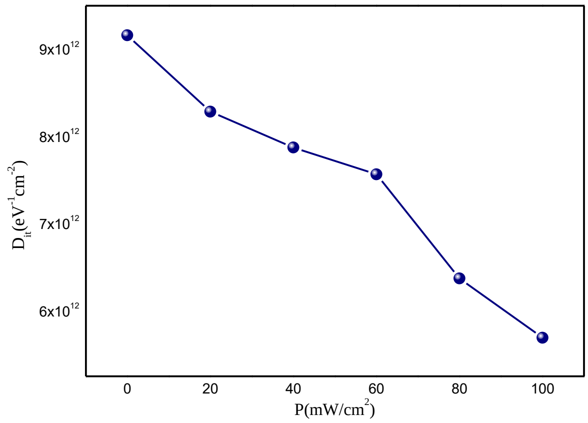

Fig. 10. *Plot of the interface trap density Dit vs. P for the Pentacene thin film phototransistor.*

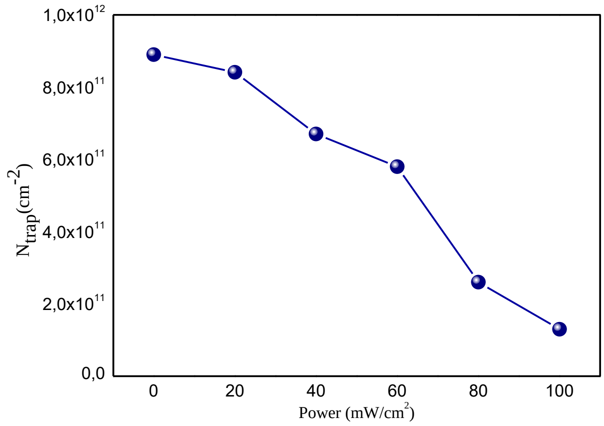

Fig. 11. *Plot of trap density Ntrap vs. P for the Pentacene thin film phototransistor.*

The current modulation (Ion/Ioff) values of the Pentacene thin film transistor under dark and white light illuminations were determined from the plot of log Ids vs. Vg under Vds = -14 V as shown in Fig. 8 and were given in Table 1. As seen in Fig. 9, the Ion/Ioff values of the Pentacene thin film transistor are increased with light white illumination, that is, Ion/Ioff values of the Pentacene thin film phototransistor under white illumination (3.03×103 under 100 mW/cm2) are higher than that of the value under dark 1.33×103.For the performance of any organic thin film transistor, another important parameter is the sub-threshold swing. The sub-threshold swing value S is a measure of the turn-on speed of the transistor and it indicates the presence of trap behavior and interface quality between the dielectric and active layer [25, 26]. The S value of the transistor controls the voltage swing that is required to turn a transistor from “off” to “on” state and it can be determined by the following relation [25],

$$S = \left(\frac{dlog(I_d)}{dV_g}\right)^{-1} \qquad (7)$$

The S values of the Pentacene transistor under dark and white light illuminations were determined by means of Fig. 9 and are given in Table 1. As seen in Table 1, the S value under dark is higher than that of under white light illuminations. This suggests that density of traps at the interface is decreased by white light illumination, because the SS value indicates the presence of trap behavior and interface quality between the SiO2-PVP dielectric and Pentacene active layer. As seen in Table 1, the Pentacene thin film phototransistor gives the higher mobility with a smaller S value, which exhibits the better performance. The sub-threshold behavior of the drain current is attributed to the distribution of defect states in the band gap. The interface trap density for the transistor can be determined by the following relation [23, 27]:

$$D_{it} = \left[\frac{Slog(e)}{kT/q} - 1\right]\frac{C_i}{q} \qquad (8)$$

Where k is the Boltzmann constant, q is the electronic charge and T is the temperature. With Ci and S value, the Dit values of the Pentacene transistor under dark and white light illuminations were determined and are given in Table 1.

Table. 1. The threshold voltage Vth, mobility, ION/IOFF ratio and subthreshold swing, interface trapped density Dit and the total trapped density Ntarp values of the Pentacene thin film phototransistor under dark and white light illumination.

P (mW/cm^2)	**V_{th} (V)**	**μ(×10^{-3}cm^2/Vs)**	**I_{ON}/I_{OFF}**	**S(V/decade)**	**D_{it}(×10^{12} eV^{-1}cm^{-2})**	**N_{trap}(×10^{11} cm^{-2})**
0	-4.12	8.5	1330	2.53	9.2	8.9
20	-3.90	9.2	1650	2.288	8.3	8.4
40	-3.09	10	1830	2.175	7.9	6.7
60	-2.69	10.3	2010	2.09	7.6	5.8
80	-1.19	10.8	2810	1.76	6.4	2.6
100	-0.59	11.2	3030	1.572	5.7	1.3

The plot of Dit vs. illumination intensity is shown in Fig. 10. As seen in Fig. 10, the interface trap density of the Pentacene phototransistor is decreased with increasing illumination. This indicates that the numbers of charges at the interface are decreased by illumination, because they contribute to the photocurrent. As seen in Table 1, the lowest Dit value (5.7× 10^{12} eV^{-1} cm-2) of the Pentacene thin film phototransistor causes the highest mobility (1.12× 10^{-2} cm^2/Vs). The changing in Dit values can be due to the photoexcitation of trapped holes into transport states at the interface [23].As seen in Table 1 and Fig. 7(a), the Vth values of the Pentacene thin film transistor change with dark and white light illuminations. The total trap density for the transistor can be determined by the following relation [28],

$$N_{trap} = c_i \frac{|\Delta V_{th}|}{q} \qquad (9)$$

The Ntrap values of the Pentacene thin film phototransistor under dark and white light illuminations are calculated via Eq. (9) and are given in Table 1. The plot of Ntrap vs. illumination intensity is shown in Fig. 11. As seen in Fig. 11, the Ntrap values of the Pentacene phototransistor are decreased with increasing illumination intensity, because the trapped carrier charges escape from traps level in the organic semiconductor with illumination and thus, the number of photogenerated charges increases and therefore, the Ntrap values are decreased with illumination, $9\times10^{11}$and 1.3×10^{11} eV/cm^2 under dark and 100 mW/cm^2, respectively.

An important parameter of photoresponsive organic thin film transistors is photoresponsivity and it is expressed by the following relation [29]:

$$R = \frac{I_{photo}}{P_{opt}} = \frac{(I_{ill} - I_{dark})}{P.A} \qquad (10)$$

Where I_{ph} is the drain-source photocurrent, P_{opt} is the incident optical power, P is the power of the incident light per unit area, Iill is the drain–source current under illumination, Idark is the drain-source current under dark and A is the effective device area. The R values of the PVP-Pentacene transistor under dark and white light illuminations were determined from Eq. (10) and plotted in Fig.12.

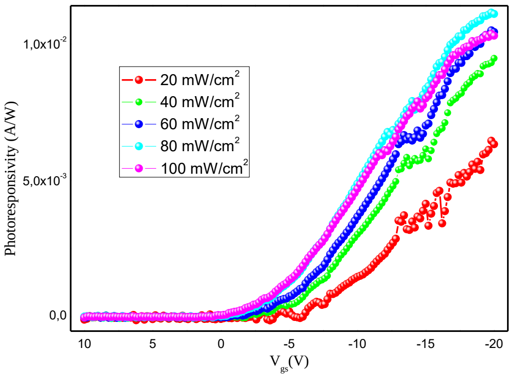

Fig. 12. *Plot of photreponsivity vs. Vg for the Pentacene thin film phototransistor.*

As seen in Fig.12, the R values of the PVP-Pentacene thin film phototransistor are varied from 6.32 mA/W to 10.9 mA/W. The illumination increases the R values of the Pentacene phototransistor.

For analysis of the operation mechanism of the transistor, we used the following relation [30],

$$I_{ds} = kV^m \qquad (11)$$

Where k is a constant and m is a exponent determining the charger transport mechanism. The Fig. 13 shows the double logarithmic scale.

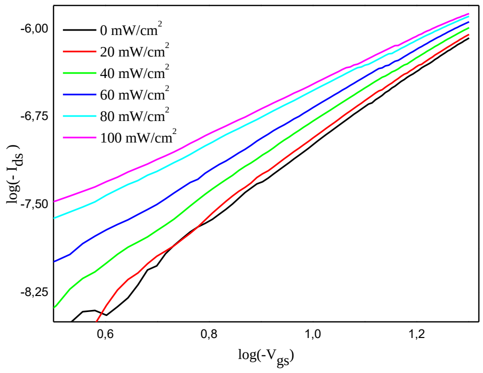

Fig. 13. *Plot of the log(-Ids) vs. log(Vg) of the Pentacene thin film phototransistor under white light illumination.*

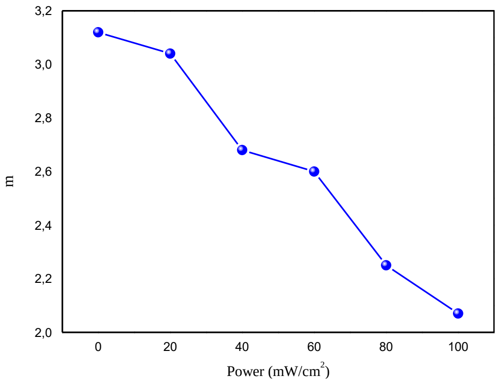

Fig. 14. *Plots of m vs. P of Pentacene thin film phototransistor.*

As seen in Fig. 13, at higher voltages, the curves of logI vs. logV plotted shows one linear region suggesting that the current transport mechanism is controlled by one charge transport mechanism. m values were determined from plot of logI vs. logV, as shown in Fig. 14. As seen in Fig. 14, the m values decrease with visible light illumination. The m value decreases with increasing illumination intensity. This indicates that the carrier charges are escaped from the traps levels in the organic semiconductor and they make a contribution to drain current and in turn, the drain current increases with illumination. At higher illumination, m values reach to be 2.07 and this suggests that the charge transport mechanism is controlled by space charge limited current mechanism.

4. Conclusion

We have investigated the effect of white light illuminations on the electrical and photosensing properties of the Pentacene thin film phototransistor. The electrical parameters such as mobility, threshold voltage, sub-threshold swing value, photosensitivity, photoresponse, Ion/Ioff ratio, interface trap density, total trap density and photoresponsivity were changed by white light illuminations. The mobility values of the PVP-Pentacene thin film phototransistor are increased from 8.5× 10^{-3} cm^2/Vs to 1.2× 10^{-2} cm^2/Vs with increasing illumination intensity from dark condition to100 mW/cm^2. The threshold voltage values of the PVP-Pentacene thin film phototransistor is varied from -1.29 V to 0.525 V with light illumination. The sub-threshold swing value under dark is higher than that of under white light illuminations. The interface trap density of the Pentacene thin film phototransistor is decreased with increasing illumination. The lowest Dit value (1.3× 10^{11} eV^{-1} cm^{-2}) of the PVP-Pentacene thin film phototransistor caused by the highest mobility (1.12× 10^{-2} cm^2/Vs). The total trap density Ntrap values of the PVP-Pentacene phototransistor are decreased with increasing illumination intensity. The photoresponsivity R values of the Pentacene thin film phototransistor are varied from 16.32 mA/W to 10.9 mA/W. The illumination increases the R values of the Pentacene thin film phototransistor. The obtained results indicate that the Pentacene phototransistors could find use in photodetector applications.

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